2014 Workshop on Thermionic Energy Conversion for Space and Earth

October 14-15, 2014

NASA Johnson Space Center

Houston, TX

Organizers:

Jeffrey A. George
EP/Propulsion and Power Division
NASA Johnson Space Center

Prof. David B. Go
Aerospace and Mechanical Engineering
University of Notre Dame

Getting Started

- Welcome
- Introductions
- Purpose, Goals, Objectives
- Logistics
- Discussion Guidelines
- Agenda
- Breakout Sessions
- Reporting, Next Steps

Attendees

	Name	Org	Email
NASA/JSC (not traveling)			
1	Jeff George	NASA/JSC	George, Jeffrey A. (JSC-EP311) <jeffrey.a.george@nasa.go
2	Jason Wolinsky	NASA/JSC	WOLINSKY, JASON J. (JSC-EP311) <jason.j.wolinsky@nasa.g
3	Eric Malroy	NASA/JSC	Malroy, Eric T. (JSC-ES411) <eric.t.malroy@nasa.gov>
4	Jonette Stecklein	NASA/JSC	Stecklein, Jonette M. (JSC-YX111) <jonette.m.stecklein@n
5	John Scott	NASA/JSC	Scott, John H. (JSC-EP311) (john.h.scott@nasa.gov)
6	John Alred	NASA/JSC	Alred, John W. (JSC-ES411) <john.w.alred@nasa.gov>
7	Paul Bailey	NASA/JSC/Wyle	BAILEY, PAUL S. (JSC-EP3)[WYLE INTEG. SCI. & ENG.] <paul.s
NASA/MSFC, JPL, U.S. Army, U.S. Air Force (traveling)			
8	Mike Houts	NASA/MSFC	Houts, Michael G. (MSFC-ZP30) <michael.houts@nasa.gov>
9	Jean-Pierre Fleurial	NASA/JPL	Fleurial, Jean-Pierre (JPL-3464)[Jet Propulsion Laboratory]
10	Joshua Smith	United States Army Research Laboratory	Smith, Joshua CTR (US) <joshua.smith133.ctr@mail.mil>
11	Steve Fairchild	AFRL/Wright Patterson	Steven.Fairchild@us.af.mil
US Institutions (Academic & Commercial)			
12	David Go	University of Notre Dame	David Go (dgo@nd.edu)
13	John Haase	University of Notre Dame	John Haase (jhaase1@nd.edu)
14	Timothy S. Fisher	Purdue University	tsfisher@purdue.edu
15	Terence Musho	West Virginia University	Terence.Musho@mail.wvu.edu
16	Robert Nemanich	Arizona State University	Robert.Nemanich@asu.edu
17	Franz Koeck	Arizona State University	franz.koeck@asu.edu
18	"Nick" Nicholas A. Melosh	Stanford University	nmelosh@stanford.edu
19	Tony Pan	Invention Science Fund	Tony Pan - Individual <tpan@intven.com>
20	William (Hank) Paxton	IOP Technologies, LLC	William Paxton <william.f.paxton@gmail.com>
Non-US Institutions (Academic & Commercial)			
21	Alireza Nojeh	University of British Columbia	anojeh@ece.ubc.ca
22	Neil Fox	University of Bristol	neil.fox@bristol.ac.uk
23	Ian Bickerton	University of Bristol	Ian Bickerton <Ian.Bickerton@bristol.ac.uk>
24	Amit Tiwari	Newcastle University, UK	amit.tiwari@ncl.ac.uk
25	Jochen Mannhart	Max Planck Gesellschaft	J.Mannhart@fkf.mpg.de
26	Robin Wanke	Max Planck Institute of Solid State Research	Robin Wanke <R.Wanke@fkf.mpg.de>

Workshop Announcement

2014 Workshop on Thermionic Energy Conversion for Space and Earth

October 14-15, 2014
NASA Johnson Space Center
Houston, TX

The Propulsion and Power Division of NASA Johnson Space Center is hosting a workshop on the research and development of thermionic energy conversion to power future space missions and terrestrial applications. Currently, NASA has a vision to send manned missions to Mars in the 2030's. However to do so, new power and propulsion technologies must emerge that have the capability of greatly reducing round trip time and initial launch mass. Thermionic energy conversion has the potential for high efficiency, "solid-state" operation with no moving parts, and could form the foundation of future power systems with high specific power, high reliability, and greatly reduced complexity and cost. Building upon the lessons, art, flight experience and discovered challenges of the 1960's-1990's, modern advances in nanotechnology, materials, and microfabrication may now enable thermionic converters to achieve their potential for space and terrestrial power.

The purpose of this workshop is to bring together intellectual leaders and others interested from academia, the U.S. military, U.S. government labs, and industry to restart the conversation on using thermionic energy conversion for space applications. The goals of the workshop are:

- To foster an intellectual and research community in thermionic emission and thermionic energy conversion focused on the development of thermionic energy conversion devices for space applications;
- To identify rationale that could lead to a larger sponsored research program, potentially in conjunction with other U.S. research agencies.

This two-day workshop will consist of both invited and contributed talks and brainstorming sessions centered around four themes:

1. Applications, need, requirements, and historical development

2. New and emerging cathode and anode materials for high current density thermionic energy conversion (doped diamond, carbon nanotubes, barium oxide, etc.)

3. New and emerging form factors and designs for thermionic energy conversion devices (microfabricated structures, diode/triode configurations, photo-enhanced thermionic emission, etc.)

4. Testing and characterization apparatus and standards for material characterization, device performance and efficiency, and lifetime and robustness tests

There is no registration fee, but attendees are required to cover their own travel and lodging expenses. There are a limited number of open slots for the workshop, and registration will be granted on a first come basis. To register interest and potential presentation title/abstract, please contact the organizers:

Jeffrey George (jeffrey.a.george@nasa.gov)
EP/Propulsion and Power Division
NASA Johnson Space Center, Houston, TX 77058

Prof. David B. Go (dgo@nd.edu)
Aerospace and Mechanical Engineering
University of Notre Dame, Notre Dame, IN 46556

Workshop Purpose & Goals

Purpose: **In light of recent advances in materials, nanotechnology, and microfabrication, to bring together interested parties from government, academia, and industry to "restart the conversation" on using thermionic energy conversion for Space and Earth applications.**

Major Goals:

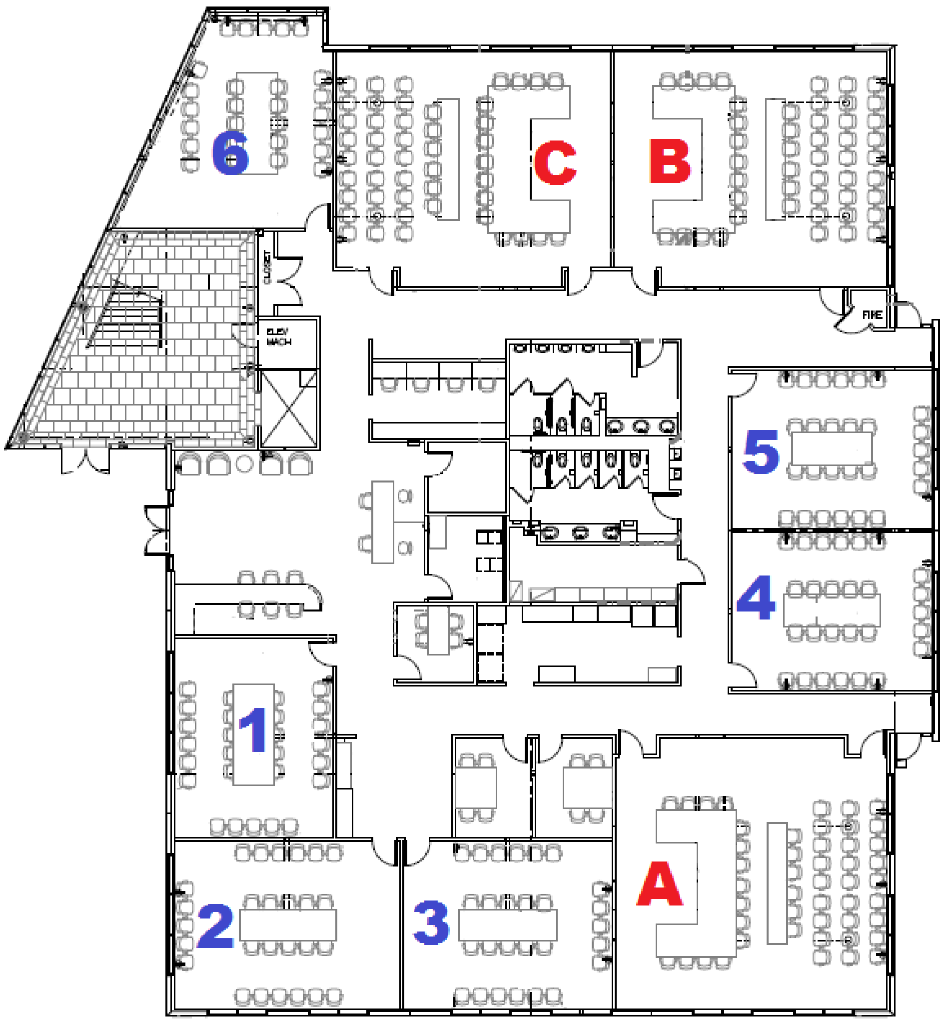
- **To foster a collaborative intellectual and research community in thermionic emission and energy conversion**
- **To identify and describe promising applications and "need"**
- **To identify rationale and recommendations for focused research**
- **To communicate recommendations to stakeholders and policymakers**
- **To have effected and advanced the realization and implementation of practical thermionic converters**

Workshop Topical Areas:

- **Applications, need, requirements, and historical development**
- **New and emerging cathode and anode materials for high current density thermionic energy conversion (doped diamond, carbon nanotubes, barium oxide, etc.)**
- **New and emerging form factors and designs for thermionic energy conversion devices (microfabricated structures, diode/triode configurations, photo-enhanced thermionic emission, etc.)**
- **Testing and characterization apparatus and standards for material characterization, device performance and efficiency, and lifetime and robustness tests**

Logistics

- **ISS Facility Badging, Rules**
  - **Visitors badge**
  - **Core hours 8:00am-5:00pm**
- **Wireless**
- **Emergencies**
- **Break room**
- **Restrooms**
- **Lunch**
- **Tuesday Dinner**
  - **Landry's, Kemah Boardwalk**
- **Saturn V?**
- **Wednesday Dinner?**
- **Space Center Houston?**



Discussion Guidelines

- Public meeting, information, discussion
- International attendance
- Export Control rules apply for US attendees
  - Limit discussions to cleared or publicly available info
- Mind the clock (so we can cover as much ground as possible)
  - 30 min slots
  - ~20 min presentation
  - ~10 min Q&A, discussion

ROM Primary Focus

Thermionic Energy Conversion for Space Missions
Jeff George, NASA
Michael Houts, NASA
Jean-Pierre Fleurial, JPL

Emerging Thermionic Emission Materials
Tim Fisher, Purdue University
Nicholas Melosh, Stanford University
Terrence Musho, West Virginia University
Steven Fairchild, AFRL

Emerging Thermionic Energy Conversion Devices
*Jochen Mannhart, Max Planck Institute
*Alireza Nojef, University of British Columbia
Joshua Smith, Army Research Lab
Tony Pan, Invention Science Fund
David Go, University of Notre Dame

Diamond-Based Thermionic Energy Conversion
Neil Fox, University of Bristol
Hank Paxton, IOP Technologies
*Robert Nemanich, Arizona State University
Amit Tiwari, Newcastle University

Commercial
Academia
Government
*Breakout Session Leader

Agenda

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Tuesday, October 14, 2014

8:00 – 8:30 a.m. Continental breakfast

8:30 – 8:45 a.m. Welcome, Overview, and Anticipated Outcomes of Workshop
Jeffrey George, NASA and *David Go, University of Notre Dame*

Session I:	**Thermionic Energy Conversion for Space Missions**
8:45 – 9:15 a.m.	Jeffrey George, NASA Johnson Space Center "Thermionic Emission and the Mission to Mars"
9:15 – 9:45 a.m.	Michael Houts, NASA Marshall Space Flight Center "Thermionic Programs of the Early 1990s – TFEVP and Flight Topaz"
9:45 – 10:15 a.m.	Jean-Pierre Fleurial, NASA Jet Propulsion Laboratory "RTG's, Thermoelectrics, and Thermionics"

10:15 – 10:30 a.m. Coffee Break

Session II:	**Emerging Thermionic Emission Materials I**
10:30 – 11:00 a.m.	Timothy Fisher, Purdue University "Thermionic and Photo-excited Electron Emission from 2D Materials"
11:00 – 11:30 a.m.	Nicholas Melosh, Stanford University "Heterostructures for Improved Photon Enhanced Emission (PETE) for Solar Thermal Energy Conversion"
11:00 – 12:00 p.m.	Terrence Musho, West Virginia University "Understanding the Role of Confined Carriers in Nanotipped Thermionic Emitters"

12:00 – 1:15 p.m. Lunch

Session III:	**Emerging Thermionic Energy Conversion Devices I**
1:15 – 1:45 p.m.	Jochen Mannhart, Max Planck Institute "Gates: A Solution to the Space Charge Problem"
1:45 – 2:15 p.m.	Alireza Nojeh, University of British Columbia "Dimensionality, Feedback and Heat Trap for Nanostructure-based Thermionic Emission"
2:15 – 2:45 p.m.	Joshua Smith, Army Research Laboratory "Achieving 20% Absolute Efficiency with a Thermoelectron Engine using a Negative Electron Affinity Collector"

2:45 – 3:00 p.m. Coffee Break

Session IV:	**Diamond-Based Thermionic Energy Conversion I**
3:00 – 3:30 p.m.	Alon Hoffman, Technion Israel Institute of Technology "Surface Conditioning for the Enhancement of Thermionic Emission of Diamond Surfaces"
3:30 – 4:00 p.m.	Neil Fox, University of Bristol "An Overview of the Beta-Enhanced Thermionic Diamond Energy Converter"

4:00 – 4:30 p.m. Day 1 Wrap Up and Summary
Jeffrey George, NASA and *David Go, University of Notre Dame*

6:00 p.m. Group Dinner

Note: All talks are 20 min. Gordon Conference Style with 10 min. of Q&A

Wednesday, October 14, 2014

8:30 – 9:00 a.m. Continental breakfast

9:00 – 9:15 a.m. Day 2 Overview and Agenda
Jeffrey George, NASA and *David Go, University of Notre Dame*

Session V:	**Emerging Thermionic Energy Conversion Devices II**
9:15 – 9:45 a.m.	Tony Pan, Invention Science Fund "Inverse Tunneling in Field Emission Heat Engines"
9:45 – 10:15 a.m.	David Go, University of Notre Dame "Microplasmas for Enhanced Thermionic Emission"

10:15 – 10:30 a.m. Coffee Break

Session VI:	**Diamond-Based Thermionic Energy Conversion II**
10:30 – 11:00 a.m.	William (Hank) Paxton, IOP Technologies/Vanderbilt University "The Future of Diamond-Based Thermionic Energy Conversion Devices: Promise and Challenges"
11:00 – 11:30 a.m.	Robert Nemanich, Arizona State University "Thermionic and Photon-enhanced Emission from CVD Diamond and New Approaches for Energy Conversion"
11:00 – 12:00 p.m.	Amit Tiwari, Newcastle University "Diamond-based Thermotunnel Devices for Hostile Environment Energy Conversion"

12:00 – 1:15 p.m. Lunch

1:15 – 2:30 p.m. Breakout Sessions **(Will we Have Rooms?)**
The objective of the breakout sessions is to outline the key elements that will go into the Workshop Technical Report that will be published and archived as a NASA Technical Memo. The intent is for the Workshop Technical Report to cover the state-of-the-art (circa 2014), promising avenues for the future, and areas where resources should be focused to advance development. WE will nominally divide into 4 teams to outline the following topics:
- *Applications and requirements for modern and future TEC devices;*
- *Form factors and device structures for modern and future TEC devices;*
- *Material requirements for modern and future TEC devices;*
- *Testing and characterization apparatus and standards for TEC devices.*

2:30 – 2:45 p.m. Coffee Break

2:45 – 3:45 p.m. Reconvene to Discuss Breakout Sessions and Assign Writing Tasks

3:45 – 4:00 p.m. Day 2 Wrap Up and Meeting Adjourned
Jeffrey George, NASA and *David Go, University of Notre Dame*

Note: All talks are 20 min. Gordon Conference Style with 10 min. of Q&A

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Why Explore Mars?

- **Most *similar* planet to Earth. (though still different)**
- **Compare Geography, Geology, Development History**
- **Once had a warm, wet *Climate*. (What happened?)**
- **Did *Life* once exist? (Or still exist?)**
- **Humans Can Explore Mars.**
  - **Not too far or hot or cold, sunlight, gravity, resources**
- **Humanity could Live there. (a second home to Earth)**
- **Our Next Big Challenge!**
- **What will we Learn?**
- **What will we Invent?**

Mars: *The Need for Speed…*

**Increased Mission Duration →
Increased Risk, Health Concerns, Consumables, Spares**

- **Radiation**
  - **SPE**
  - **GCR**
  - **(Reactor)**
- **Depressed Immune System**
- **Bone Loss**
- **Muscle Loss**
- **Away from Family, Friends, Joys of Life**
- **Mental Well Being / Morale**
- **Catastrophic Environmental Events**
- **System Failures (&/or massive redundancies/spares to mitigate)**
- **Increased Food & Consumables load**
- ***<Good Thing → Power-rich can enable 3D printers to make spares, better/lighter ECLSS S/S's, etc.>***

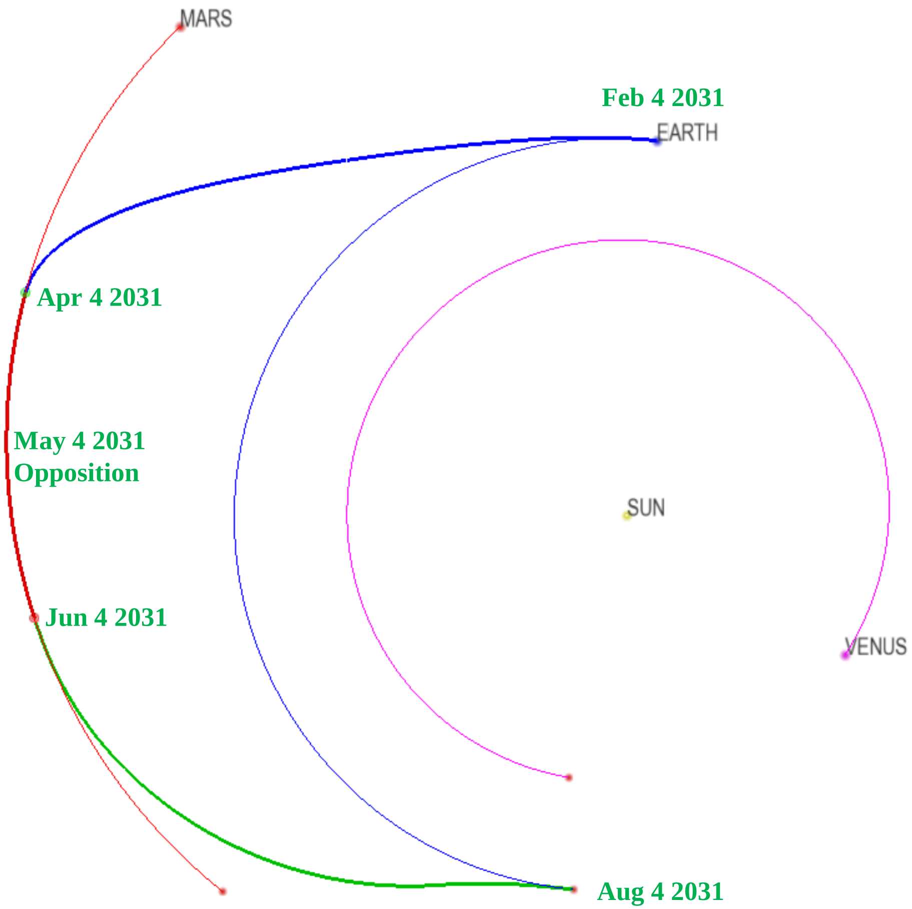
If we can't find a way to break the 3.5 year Mars mission paradigm, we may <u>never</u> get to Mars.

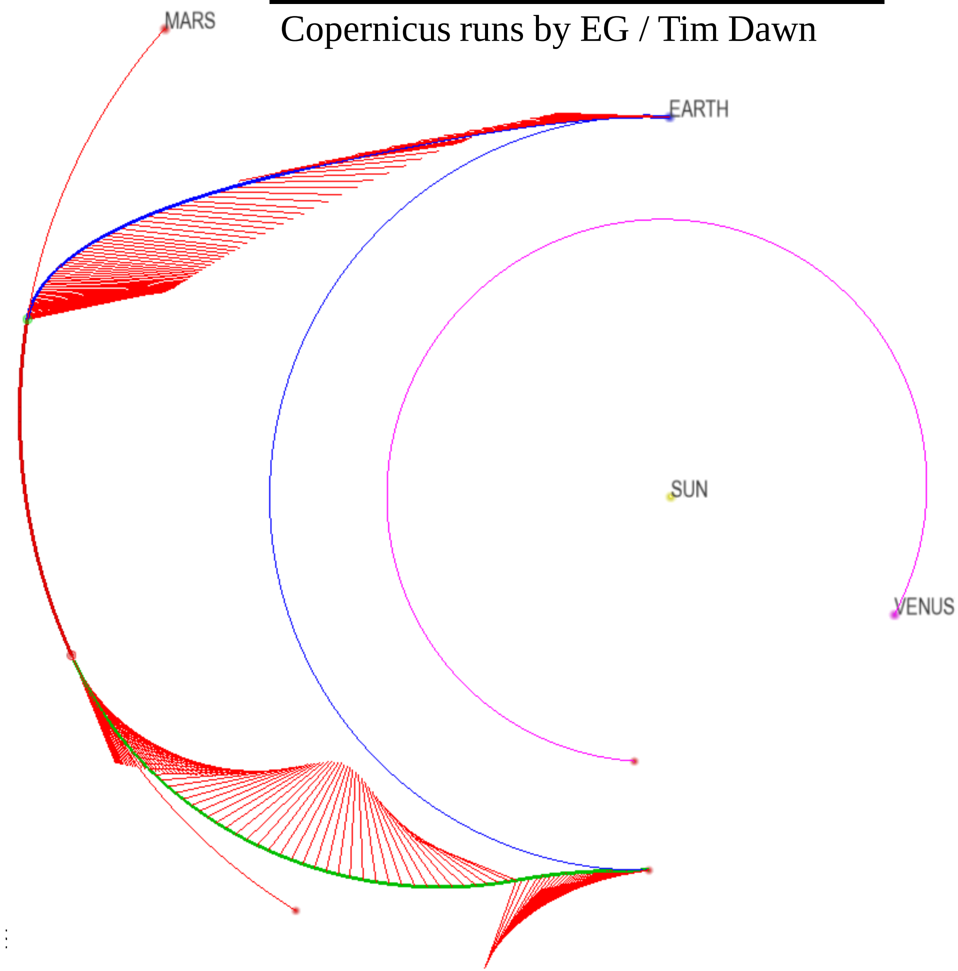
Six Month Mars Mission: Case 1 Q-thruster

- 2 month outbound leg (Earth SOI → Mars SOI)
- 2 month Mars stay (orbital maneuver, EDL, Surface)
- <u>2 month return leg (Mars SOI → Earth SOI)</u>
- 6 month Round Trip (Earth SOI → SOI)

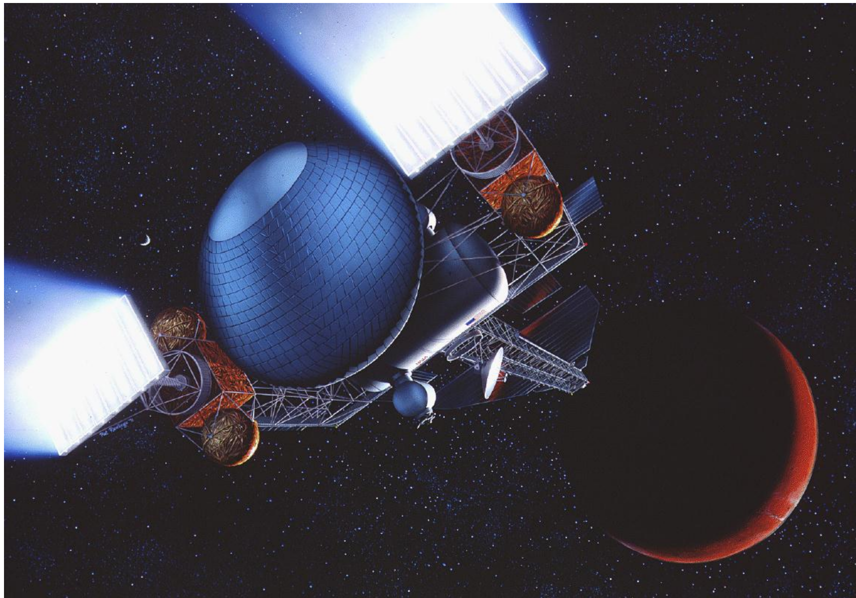
Thrust (N)	Q-thr. Metric (N/kWe)	Power (kWe)
2180	0.4	5450
2180	1	2180
2180	4	545

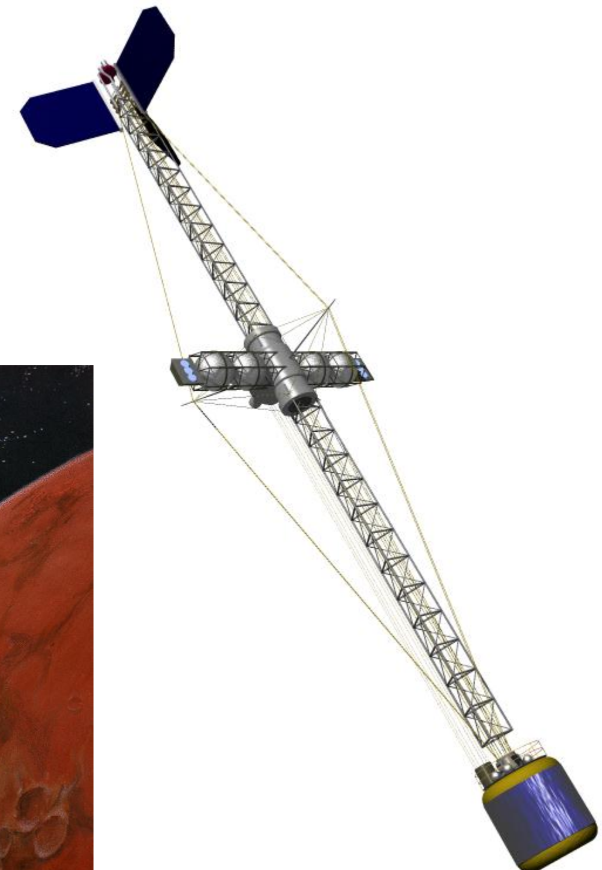
Copernicus runs by EG / Tim Dawn





Mars Vehicle Concepts

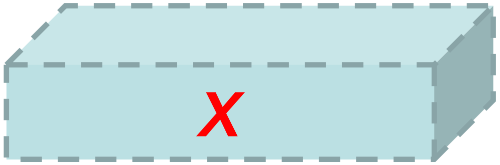




"Converter X" Design Ref. & Performance Goals

~ Initial Working Concept for Thermionic Converter:

- "Reasonable" unit scale, system quantity
- 25mm x 25mm area
- 20% system efficiency, 25% converter efficiency
- 20 We / cm^2
- 125 We converter



- Voltage = 1-2 V
- Current = 10-20 amps / cm^2
- Thot = 1600-1800 K
- Tcold = 900-1100 K
- Gap = TBD 5-10, or 100 micro-m (0.01-0.1 mm vacuum vs. mag. assist)
- Emitter Material/Surface = Nanostructured Tungsten w/ adsorbed BaO
- Emitter Work Function = 2 eV
- Collector Material/Surface = Doped diamond nano crystals
- Collector Work Function = 1 eV
- Other structural, insulating materials = Alumina
- Space Charge Mitigation = Small vacuum gap, Magnetic assist, ~~Cesium plasma~~
- Design Approach, Morphology = tbd
- Microfabrication Approach / Techniques = tbd

“21st Century” Pathways for Improvement

- New Emitter and Collector Materials with Lower Work Functions
- Nano-fabricated Surface Topologies to Lower Work Functions
- Microfabrication
- New Converter Design / Topography Approaches to Reduce or Eliminate Space Charge Effects
- Photon Enhanced Thermionic Emission (PETE)
- Others?

Thermionic Conversion Applications

***SPACE POWER*:**

- **Nuclear thermal sources**
- **Solar thermal sources**
- **Others?**

***TERRESTRIAL POWER*:**

- **“Topping” of fossil fuel plants**
- **Energy harvesting / scavenging**
- **Others?**